

1 **Linkages between climate, seasonal wood formation and**

2 **mycorrhizal mushroom yields**

3 Authors: Irantzu Primicia^{a,b}, J. Julio Camarero^c, Juan Martínez de Aragón^d, Sergio de-
4 Miguel^e and José Antonio Bonet^{d,e}

5
6
7 ^aFaculty of Forestry and Wood Sciences, Czech University of Life Sciences
8 Prague, Kamýcká 129, Praha 6–Suchbát, 16521 Prague, Czech Republic.

9 ^bDpto. Ciencias del Medio Natural, Universidad Pública de Navarra, Campus de
10 Arrosadía, Pamplona, Spain

11 ^cInstituto Pirenaico de Ecología (IPE-CSIC). Avda. Montañana 1005, 50059
12 Zaragoza, Spain

13 ^dCentre Tecnològic Forestal de Catalunya (CTFC-CEMFOR). Ctra. de St. Llorenç
14 de Morunys km 2, E-25280 Solsona, Spain

15 ^eDepartament de Producció Vegetal i Ciència Forestal, Universitat de Lleida-
16 Agrotecnio Center (UdL-Agrotecnio), Avda. Rovira Roure, 191, E-25198 Lleida,
17 Spain.

18
19 Email addresses: Primicia I. (irantzuprimicia@gmail.com)*, Camarero J.J.
20 (jjcamarero@ipe.csic.es), Martínez de Aragón J. (mtzda@ctfc.es), de-Miguel S.
21 (sergio.demiguel@pvcf.udl.cat), Bonet J.A. (jantonio.bonet@pvcf.udl.cat).

22
23 Corresponding author: Primicia, I.

© 2016. This manuscript version is made available under the **CC-BY-NC-ND 4.0 license**

<http://creativecommons.org/licenses/by-nc-nd/4.0/>

24 **Abstract**

25 Fungi provide important forest ecosystem services worldwide. In Mediterranean pine
26 forests, predicted warmer and drier conditions could lead to a decline in mushroom yields.
27 Climate is a key factor regulating both tree growth and fungal yields, particularly in drought-
28 prone Mediterranean ecosystems. However, the responses of forest growth and mushroom
29 production to climate depend on the differences among tree and fungal species and functional
30 groups (e.g., mycorrhizal vs. saprotrophic), forest types, as well as depending on site conditions.
31 Here we investigate how climatic conditions drive seasonal wood formation (earlywood –EW–
32 and latewood –LW– production) and mycorrhizal mushroom production, to disentangle if
33 growth and fungal yields are related. This assessment was done in Mediterranean forests
34 dominated by four pine species in two areas located in Catalonia (NE Spain) representing mesic
35 and xeric conditions and encompassing wide ecological gradients. The data consisted of 7-year
36 to 13-year long inventories of mushroom production. EW production was favoured by cold and
37 wet climate conditions during the previous fall and winter, and during the current spring and
38 summer. LW production was enhanced by warm and humid conditions from spring to early fall.
39 Mushroom yield was improved by wet late-summer and fall conditions, mainly in the most xeric
40 area. This study confirms the ample differences found in tree growth and fungal production
41 along ecological and climatic gradients. Clear relationships between mycorrhizal fungal yields
42 and tree growth were mostly observed in specific sites characterized by severe summer drought.
43 Specifically, latewood production seems to be the tree-ring variable most tightly linked to
44 mycorrhizal fungal yield in drought-prone areas.

45

46 **Keywords:** drought, tree growth, pine, forest, fungi, dendroecology.

47

48 **Abbreviations:** PS, *Pinus sylvestris*; PN *Pinus nigra*; PH, *Pinus halepensis*; PP, *Pinus pinaster*;
49 EW, earlywood width; LW, latewood width; DBH, diameter at breast height; PET, potential
50 evapotranspiration rate; P, precipitation; MFY, mycorrhizal fungi yield; CV, coefficient of
51 variation.

52 **1. Introduction**

53 Climate plays a major role on the production and diversity of fungal communities, being
54 precipitation, temperature and moisture key drivers for mushroom fruiting (Boddy et al., 2014;
55 Pinna et al., 2010). In temperate and boreal forests, delayed fungal fruiting in fall or decreased
56 fungal yield have been generally related to warmer and drier years, respectively (Kausrud et
57 al., 2008; Diez et al., 2013). In Mediterranean pine forests, reduced mushroom yields usually
58 correspond to more severe dryness during summer and autumn (Ágreda et al., 2015; Büntgen et
59 al., 2015). Contrastingly, there is evidence of longer fruiting season and increased fungal
60 production in temperate Central European forests due to rising temperatures (Büntgen et al.,
61 2012, 2013). These diverse findings suggest that fungal yields are differently driven by climate
62 depending on local site conditions (e.g., topography, soil properties) and forest stand dynamics
63 (e.g., basal area, tree growth, Bonet et al., 2012, 2010, 2004; de-Miguel et al., 2014; Martínez-
64 Peña et al., 2012; Tahvanainen et al., 2016). Nevertheless, when investigating fungal production
65 as related to climate and forest growth, clear trends and associations between these three
66 components are rarely observed, probably because of differences between functional fungal
67 groups, forest types, climatic conditions and methodological issues affecting fungal records
68 (Boddy et al., 2014).

69 The symbiotic associations formed by mycorrhizal fungi with tree roots enhance the
70 transfer of soil nutrients to trees, while organic carbon compounds fixed by trees are derived to
71 fungi (Gerdemann, 1970). The phenology and photosynthetic activity of the host tree and its
72 response to climate may also influence differently mycorrhizal and saprotrophic fungal fruiting
73 arising from their differential dependence on climate conditions (Boddy et al., 2014).
74 Additionally, the sensitivity of mycorrhizal fungi to climate may depend on the tree-fungi
75 associations and the strength of those relationships (e.g. deciduous *vs.* coniferous tree species,
76 Gange et al., 2007). Nevertheless, links between the type of tree host species and the phenology
77 of mushroom fruiting have been detected in some cases (Dickie et al., 2010) whilst in others no
78 association has been found (Pinna et al., 2010).

79 Tree radial growth may be used as a proxy of carbon availability to trees since wood
80 formation has a low allocation priority compared to shoot development (Fritts, 2001). The study
81 of tree-ring features for ecological purposes (dendroecology) is therefore a powerful tool to
82 understand how coupled long-term climatic conditions, forest growth, and mushroom
83 production are (Büntgen and Egli, 2014). Mycorrhizal fungal production has been indeed
84 associated with tree growth in thinning experiments (Egli et al., 2010). However, since the
85 production of mushroom fruiting bodies is apparently highly dependent on current
86 photosynthates (Högberg et al., 2008), mycorrhizal mushroom yield could be related to seasonal
87 wood production as, in conifers, the latewood is mostly formed by current-year
88 photoassimilates, while the earlywood contains carbohydrates synthesized from the previous
89 summer and fall and current spring (Kagawa et al., 2006). Therefore, observational studies
90 aiming to relate climate, wood and mycorrhizal fungal production should consider the main
91 climatic constraints of tree growth and fungal fruiting, and the phenological patterns of both
92 processes which are linked to carbon synthesis and use within the tree. For example, these
93 studies should consider that both mycorrhizal mushroom production and latewood formation
94 usually peak during summer and autumn in most conifers of the Northern Hemisphere and
95 therefore, these two variables could be coupled to some degree.

96 In this framework, we propose assessing the potential of tree rings to investigate the long-
97 term relationships between climate conditions, seasonal wood formation (earlywood and
98 latewood widths), and mycorrhizal mushroom production. We argue that mycorrhizal and
99 saprotrophic fungal production during fall, when maximum yields are recorded in the Northern
100 Hemisphere, must be separately considered based on their different dependence on climate (Egli
101 et al., 2010). Our main objectives are (1) to determine the main climate variables influencing
102 seasonal wood formation and mycorrhizal fungal productions, and (2) to analyse whether the
103 production of mycorrhizal fungi is related to earlywood and latewood production. Our working
104 hypothesis are that: (1) earlywood formation will be influenced by spring climatic conditions
105 whilst latewood formation will be more dependent on late-summer and fall climate; (2) annual
106 mycorrhizal fungi yields will be mainly influenced by late-summer and fall climate conditions,

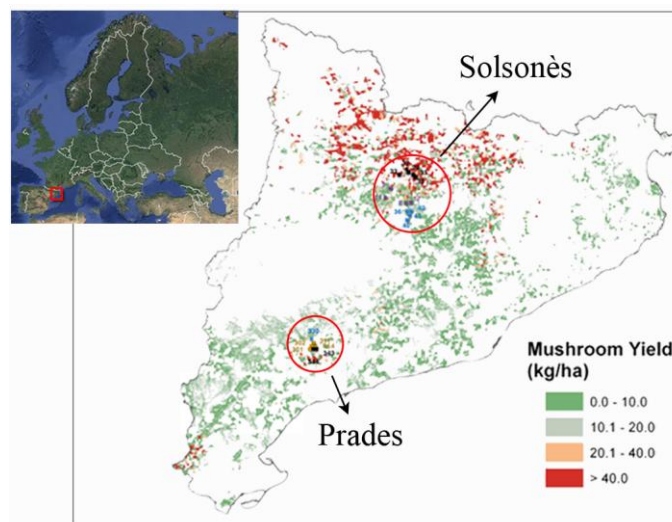
107 when fungi fruiting peaks; (3) the influence of water availability on both wood (earlywood and
108 latewood widths) and mycorrhizal mushroom production will be stronger in the most xeric sites;
109 and (4) latewood width, and not earlywood production, will be related to mycorrhizal fungi
110 yield as a function of late summer to fall climatic conditions.

111

112 **2. Material and Methods**

113 **2.1. Study area**

114 The study was conducted in monospecific stands of the most common pine forest
115 ecosystems found in Catalonia, NE Spain (*Pinus sylvestris* L., *Pinus nigra* J.F. Arnold, *Pinus*
116 *halepensis* Mill. and *Pinus pinaster* Ait.). We selected two areas subjected to different climatic
117 conditions (Solsonès and Prades) for sampling (Fig. 1). The plots in Solsonès area corresponded
118 to natural stands, whereas the Prades plots were placed on pine plantations established in the
119 1960s. Of the total of 107 permanent plots currently monitored for the annual mushroom yield
120 estimation (de-Miguel et al., 2014), we sampled nineteen stands (13 stands in Solsonès and 6
121 stands in Prades) located between 530 and 1502 m a.s.l., corresponding to highly productive
122 fungal areas (Table 1). Therefore, total mushroom yields from the selected sample plots need to
123 be considered with care inasmuch as they may not be necessarily representative of the expected
124 productivity of a typical forest stand.



125

126 **Figure 1.** Map of mean annual mushroom yields obtained for Catalonia showing its location
127 within Europe and the sampled sites in the Solsonès and the Prades study areas (Adapted from
128 Bonet et al., 2014).

129

130 The Solsonès area is subjected to continental and sub-Mediterranean conditions, with a
131 mean annual temperature of 11.1 °C and a mean annual precipitation of 726 mm, whereas the
132 Prades area experiences a stronger Mediterranean influence, i.e. a more intense drought stress
133 during the growing season (mean annual temperature of 12.1 °C and mean annual precipitation
134 of 564 mm). For each plot, physiographic and stand attributes such as slope, aspect, elevation,
135 tree density and basal area were also recorded (cf. Table 1).

136

137 **Table 1.** Summary of the plot characteristics data and mushroom yield (fresh weight) measured in Catalanian pine forests, NE Spain. Values of stand
 138 variables are means (ranges are given between parentheses).

139

Site	Pine species (code)	No. sampled plots	Period of fungi data (No. years)	Tree density (No. trees ha ⁻¹)	Stand basal area (m ² ha ⁻¹)	Altitude (m a.s.l.)	Aspect (°)	Slope (%)	Mushroom yield (kg ha ⁻¹ yr ⁻¹)		
									Mycorrhizal fungi	Saprotrophic fungi	Total
Solsonès	<i>P. sylvestris</i> , Scots pine (PS)	5	1997-2001 (5) 2007-2014 (8)	1453 (552 - 3893)	21.1 (11.1 - 30.2)	1033 (854 - 1502)	156 (63 - 282)	24 (17 - 33)	79.1 (0 - 286.5)	2.4 (0 - 20.4)	81.5 (0.2 - 307)
	<i>P. nigra</i> , Black pine (PN)	4	1997-2001 (5) 2007-2014 (8)	1613 (1100 - 2292)	26.2 (15.3 - 41.7)	773 (630 - 1040)	188 (14 - 317)	11 (5 - 19)	105.1 (0 - 472.7)	2.6 (0 - 21.4)	107.8 (0 - 474.7)
	<i>P. halepensis</i> , Aleppo pine (PH)	4	1997-2001 (5) 2007-2014 (8)	1905 (281 - 3883)	24.2 (16.4 - 31)	613 (530 - 661)	243 (170 - 292)	16 (10 - 34)	38 (0 - 281.2)	4.2 (0 - 63.6)	42.2 (0 - 293.2)
Prades	<i>P. sylvestris</i> , Scots pine (PS)	2	2008-2014 (7)	1066 (541 - 1592)	49.7 (48.3 - 51.1)	853 (841 - 864)	325 (310 - 340)	13 (8 - 18)	228.5 (0 - 551.2)	21.4 (0 - 87.3)	249.9 (2 - 638.5)
	<i>P. pinaster</i> , Maritime pine (PP)	4	2008-2014 (7)	1088 (446 - 2552)	40.6 (21 - 80.3)	807 (594 - 1013)	154 (10 - 360)	13 (3 - 22)	79.1 (0 - 450.7)	17.3 (0 - 81)	96.4 (0.2 - 481.6)

140

141 **2.2. Data collection**

142 **2.2.1. Dendrochronological methods**

143 Around each plot where mushroom production was assessed, 10-15 dominant trees were
144 randomly selected for sampling in late 2014 and early 2015 in an area *ca.* 0.5-ha large. Two
145 radial cores per tree were extracted at 1.3 m above the ground level using a Pressler increment
146 borer. The cores were air-dried, mounted on wood boards, and polished with sandpaper grits
147 until rings were clearly visible. The wood samples were visually cross-dated. Then, earlywood
148 (EW) and latewood (LW) widths were separately measured to the nearest 0.01 mm using a
149 stereomicroscope and a Lintab sliding-stage measuring device in conjunction with TSAP-
150 WinTM software (F. Rinn, Heidelberg, Germany). EW and LW were visually distinguished
151 based on the different lumen area and cell-wall thickness of the tracheids forming each type of
152 wood. Cross-dating was verified using the COFECHA program (Holmes, 1983). We obtained
153 chronologies of EW and LW widths for each plot by averaging the values for each year across
154 the trees sampled within each plot. For each tree, we measured the diameter at breast height
155 (DBH) and estimated the age at 1.3 m by counting the number of rings of the oldest core
156 containing the pith or showing the innermost curved rings indicating proximity to the pith.

157

158 **2.2.2. Mushroom yield assessments**

159 Mushroom sampling started in 1997 in Solsonès plots, and in 2008 in Prades plots. From
160 2002 to 2006, sampling was not carried out. Mushroom production (fresh mass) and species
161 richness were inventoried every week from September to December in squared plots (10 m x 10
162 m), when most fungi fruiting occurs (Bonet et al., 2012; Martínez de Aragón et al., 2007), and
163 the collection included all sporocarps of all epigeous fungal species. All collected sporocarps
164 were identified at the species level whenever possible, even though some samples could only be
165 identified to higher taxonomic levels. Additional information on the sampling methodology can
166 be found in Bonet et al. (2012, 2010), de-Miguel et al. (2014) and Martínez de Aragón et al.
167 (2007).

168

169 **2.2.3. Climate data**

170 Monthly climatic variables (minimum, maximum and mean temperatures, and total
171 precipitation) were obtained for the 1970-2014 period from the E-OBS gridded dataset by
172 selecting the 0.25° grids including the two sampling sites (Haylock et al., 2008). We used these
173 gridded data because they were similar and more updated than other climatic data obtained from
174 interpolated Spanish databases at a finer spatial resolution (Supplementary Material, Fig.
175 A1). The potential evapotranspiration rate (PET) at each plot was estimated following
176 Hargreaves and Samani (1982) and using monthly minimum and maximum temperature using
177 the *SPEI* package (Vicente-Serrano et al., 2010, Beguería et al., 2014) in the R software (R Core
178 Team, 2015). The water balance was calculated afterwards as the difference between mean
179 monthly precipitation and PET.

180

181 **2.3. Statistical analyses**

182 The mean EW and LW series obtained for each study plot were correlated against
183 monthly minimum and maximum temperature, precipitation (P) and water balance (P-PET)
184 using bootstrapped Pearson correlation coefficients on a 13-month window from September of
185 the year prior to tree growth until October of the year of tree-ring formation. This window
186 encompasses the period climatically most relevant for pine growth in the study area (Camarero
187 et al., 2010). The statistical significance of the correlations was tested using the 95% percentile
188 range method and taking into account the presence of temporal autocorrelation in the EW and
189 LW series (Dixon, 2001). Note that we used raw EW and LW data and not detrended and
190 prewhitened indices because: (i) both variables did not show significant trends during the period
191 when overlapped with fungi yield data (1997-2014), and (ii) we aimed to preserve year-to-year
192 EW and LW variability which could be related to fungi production. We used Spearman
193 correlation, which is a non-parametric and robust rank statistic suitable for non-linear
194 associations, to analyse the response of mean annual mushroom production (mycorrhizal and
195 saprotrophic fungi yields) quantified as fresh mass ($\text{kg ha}^{-1} \text{ year}^{-1}$) to the abovementioned
196 climate variables from January to December.

197 Spearman correlation was also used to assess the relationships between mean annual
 198 mycorrhizal fungi yield (MFY) and EW and LW. We also performed partial Spearman
 199 correlations between LW and MFY controlling for climatic (cumulative precipitation from
 200 August to September) and growth effects (EW production). We investigated if the correlations
 201 between EW and LW, and MFY were modulated by the plots characteristics using linear
 202 regressions. All statistical analyses were conducted using the R statistical software (R Core
 203 Team, 2015).

204

205 3. Results

206 3.1. Tree growth patterns and responses to climate

207 Both EW and LW widths were highly variable among tree species and sites (Table 2),
 208 with highest values in the Prades *Pinus pinaster* (PP) and the Solsonès *P. sylvestris* (PS) plots,
 209 followed by the Prades PS plots, and finally, by the *P. halepensis* (PH) and the *P. nigra* (PN)
 210 plots in Solsonès area. The proportion of LW ranged from 9 to 72%, with a mean value of 28%.

211

212 **Table 2.** Descriptive statistics (age, diameter at breast height- DBH, correlation with the mean
 213 series of each forest, earlywood width- EW, and latewood width- LW) for the tree-ring width
 214 chronologies of each study plot. Values are means \pm SD.

215

Site	Pine species	Plot	Age	DBH (cm)	Correlation with Master	Mean EW for the period 1990-2014 (mm)	Mean LW for the period 1990-2014 (mm)
Solsonès	Scots pine (PS)	PS029	70 \pm 7	11.8 \pm 2.9	0.54	0.7 \pm 0.4	0.2 \pm 0.2
		PS030	73 \pm 9	12.4 \pm 1.9	0.53	0.7 \pm 0.3	0.5 \pm 0.3
		PS031	33 \pm 4	11.4 \pm 3.2	0.81	0.6 \pm 0.4	0.3 \pm 0.3
		PS032	63 \pm 7	15.9 \pm 2.8	0.61	0.6 \pm 0.2	0.3 \pm 0.2
		PS033	42 \pm 13	17.9 \pm 7.7	0.67	0.6 \pm 0.2	0.3 \pm 0.2
	Black pine (PN)	PN008	78 \pm 6	15.5 \pm 2.7	0.71	0.6 \pm 0.2	0.3 \pm 0.2
		PN009	48 \pm 3	11.6 \pm 2.1	0.73	0.5 \pm 0.1	0.2 \pm 0.2
		PN011	76 \pm 5	14.0 \pm 2.2	0.67	0.4 \pm 0.2	0.2 \pm 0.2
		PN017	93 \pm 26	14.6 \pm 4.2	0.71	0.9 \pm 0.3	0.4 \pm 0.1
	Aleppo pine (PH)	PH036	78 \pm 17	18.9 \pm 5.6	0.72	1.0 \pm 0.3	0.3 \pm 0.1
PH040		76 \pm 13	13.2 \pm 2.2	0.63	1.8 \pm 0.7	0.6 \pm 0.4	

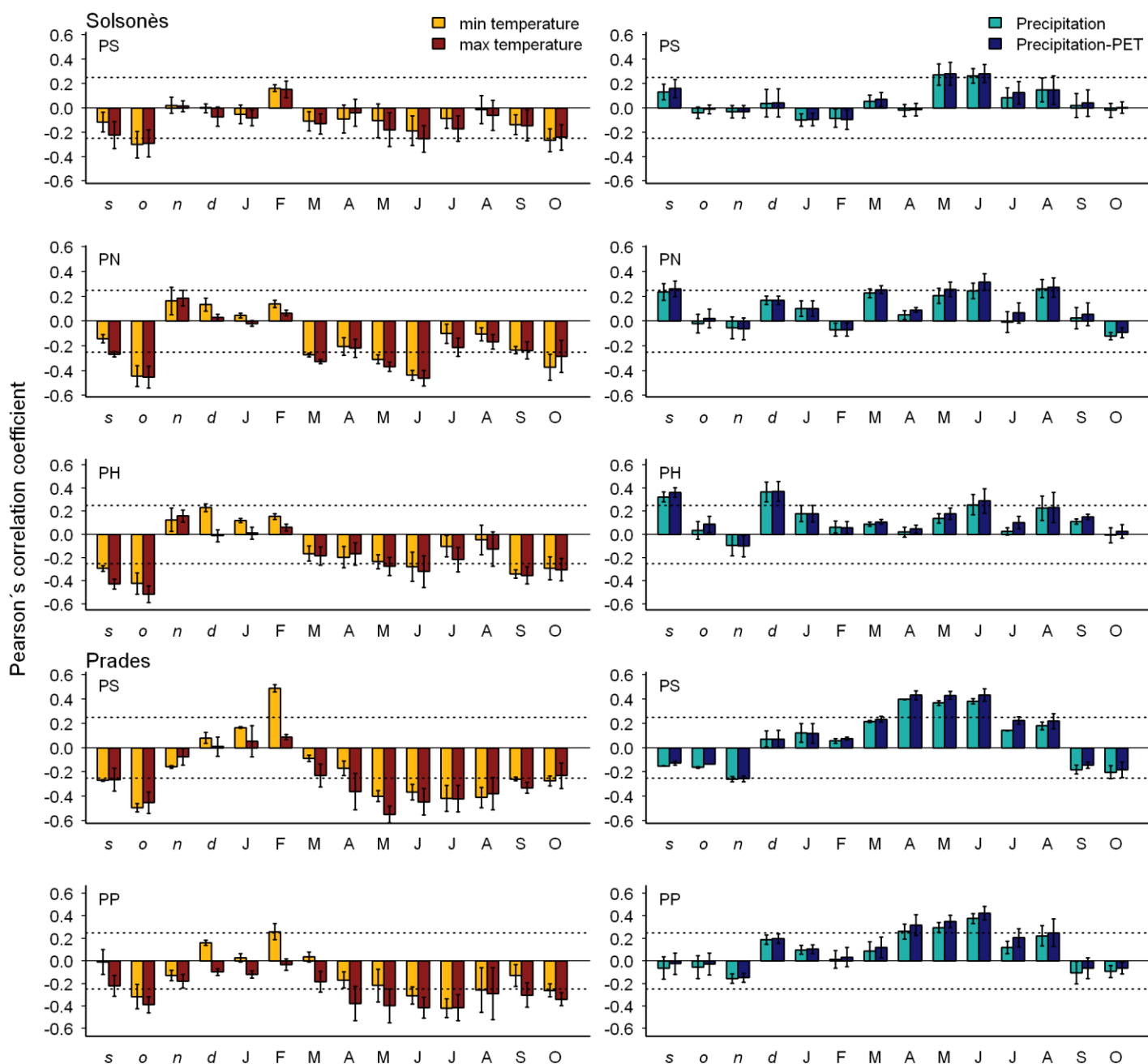
		PH041	64 ± 21	14.7 ± 3.0	0.63	1.2 ± 0.4	0.4 ± 0.3
		PH042	87 ± 13	15.3 ± 3.0	0.67	0.6 ± 0.1	0.2 ± 0.1
Prades	Scots pine (PS)	PS343	53 ± 3	16.6 ± 2.7	0.71	0.6 ± 0.1	0.2 ± 0.1
		PS344	116 ± 24	20.0 ± 4.8	0.57	1.1 ± 0.5	0.5 ± 0.4
	Maritime pine (PP)	PP301	41 ± 3	17.3 ± 2.8	0.66	0.9 ± 0.4	0.4 ± 0.2
		PP302	40 ± 2	16.6 ± 2.5	0.79	1.5 ± 0.5	0.6 ± 0.2
		PP311	35 ± 6	17.1 ± 2.3	0.76	0.7 ± 0.1	0.4 ± 0.1
		PP314	64 ± 7	20.2 ± 3.1	0.62	0.6 ± 0.1	0.2 ± 0.1

216

217 EW was more sensitive to climate conditions than LW (Figs. 2 and 3). The response of
218 EW to climate varied among tree species and study areas, except for warm conditions during
219 September and October of the previous year, which generally reduced the EW production (Fig.
220 2). EW frequently responded negatively to warm temperatures from current May to June and
221 from September to October in Solsonès, and from April to September- October in Prades.
222 Additionally, EW was enhanced by higher minimum temperature values in February in the
223 Prades plots. The sensitivity of EW to humid conditions in May- June increased towards the
224 more xeric sites (Prades), where humid conditions in April were also important. The response of
225 EW to climate variables was site-specific. Thus, while PS pines from Prades showed an EW
226 negative response to warm conditions from April to October, in Solsonès, growth of this species
227 was not affected by temperature during the year of tree-ring formation.

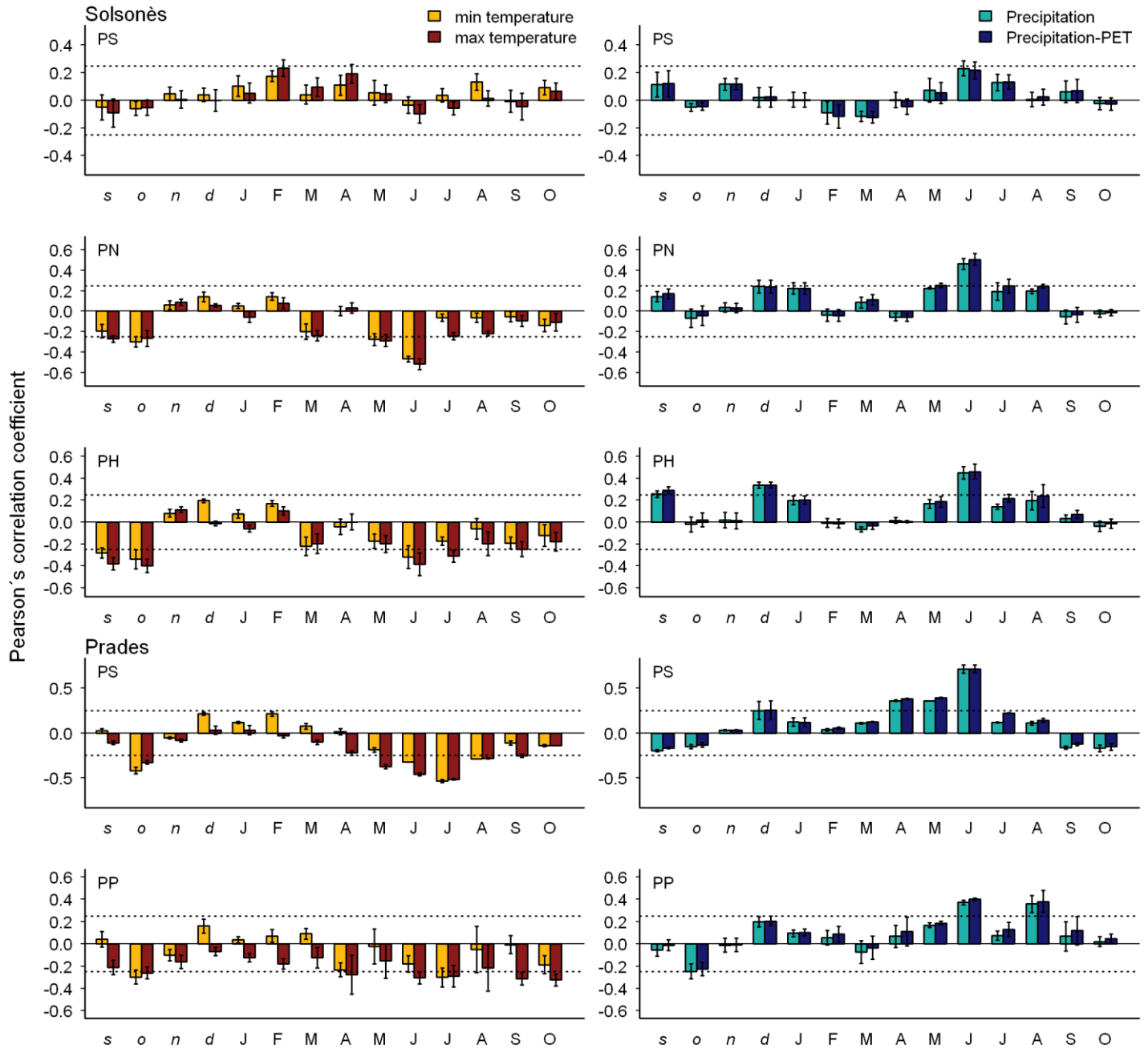
228 Warm temperatures during September and October of the previous year generally reduced
229 LW, except in the Solsonès PS plots (Fig. 3). LW also decreased with warm conditions: from
230 May to June in Solsonès PN plots; during June, July and September in Solsonès PH plots; from
231 May to September in Prades PS plots; and in April, June, July, September and October in Prades
232 PP plots. In Solsonès PN and PH plots, LW was enhanced by humid conditions in previous
233 December and current June. In Prades, LW increased with increasing water availability in
234 previous December and from April to June in PS plots, and in June and August in PP plots.
235 Again, Prades PS plots were more sensitive to climate variables in terms of LW formation than
236 those located in the less xeric Solsonès area.

237



238 **Figure 2.** Correlations (Pearson coefficients) obtained by relating earlywood width and
 239 minimum and maximum temperatures, precipitation, and water balance (precipitation minus
 240 potential evapotranspiration, PET). Months abbreviated by lowercase or uppercase letters
 241 correspond to months from the previous and current years, respectively. Horizontal dashed lines
 242 represent $P < 0.05$ significance levels. Pine species abbreviations are as in Table 1.

243



244 **Figure 3.** Correlations (Pearson coefficients) obtained by relating latewood width and minimum
 245 and maximum temperature, precipitation, and water balance (precipitation minus potential
 246 evapotranspiration, PET). Horizontal dashed lines represent $P < 0.05$ significance levels. Rest of
 247 explanations are as in Figure 2.

248

249 **3.2. Influence of climate on mushroom yields**

250 Mushroom production was highly variable among years (coefficient of variation, CV =
 251 83.1 %) and plots (CV = 68.6 %). Annual mycorrhizal fungi yield (MFY) accounted for over
 252 than 90 % of the total fungi yield. Mean MFY was 85.3 kg ha⁻¹ yr⁻¹, the values ranging from 0 to
 253 551.2 kg ha⁻¹ yr⁻¹, while the annual saprotrophic fungi yield averaged 6.1 kg ha⁻¹ yr⁻¹ and ranged
 254 from 0 to 87.3 kg ha⁻¹ yr⁻¹. The highest mushroom yields were recorded in Prades PS plots (*ca.*
 255 230 kg ha⁻¹ yr⁻¹), with maximum yearly productions exceeding 500 kg ha⁻¹ yr⁻¹ (Table 3). Years
 256 2000, 2008, 2010, and particularly, 2014, were characterized by a high production of
 257 mycorrhizal fungi, whilst years 1997, 2009 and 2013 were characterized by low fungi yields
 258 (Supplementary Material, Fig. A2). The study plots show a high fungal diversity, having
 259 collected more than 110 different mycorrhizal species in one Scots pine plot (Supplementary
 260 Material, Table A1).

261

262 **Table 3.** Mean, maximum and minimum mycorrhizal and saprotrophic fungal yield per plot (kg
 263 ha⁻¹ year⁻¹) and total number of mycorrhizal and saprotrophic identified species per plot. Pine
 264 species abbreviations are as in Table 1.

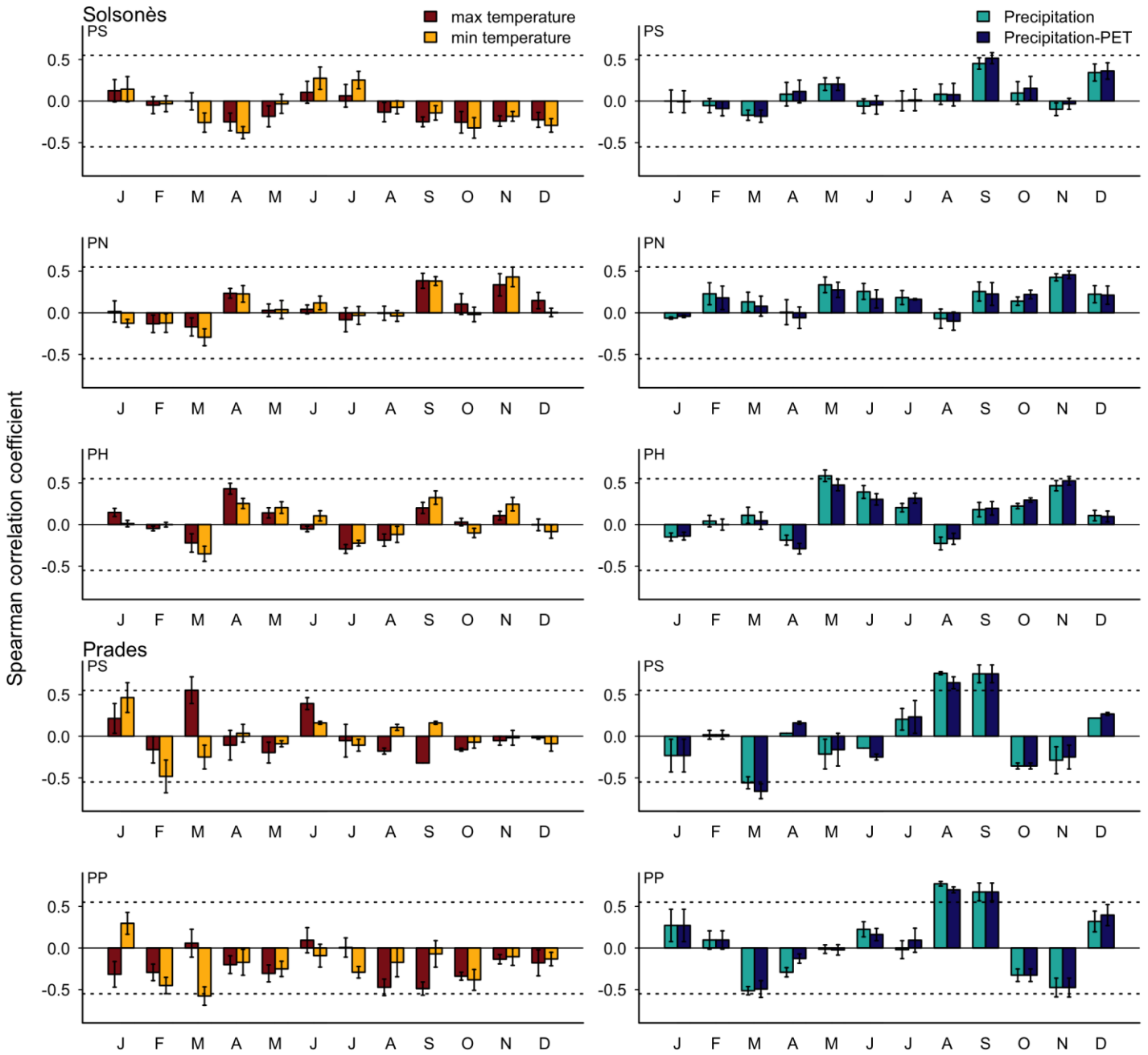
265

Site	Pine species	Plot	Mycorrhizal fungi			Saprotrophic fungi		
			Mean yield (kg ha ⁻¹ year ⁻¹)	Max-Min yield (kg ha ⁻¹ year ⁻¹)	No. species	Mean yield (kg ha ⁻¹ year ⁻¹)	Max-Min yield (kg ha ⁻¹ year ⁻¹)	No. species
Solsonès	PS	PS029	62.6	163.6-6.6	56	0.6	6.4-0.0	12
		PS030	48.1	170.5-0.0	74	1.4	9.5-0.0	32
		PS031	94.4	216.4-2.4	54	4.5	19.5-0.0	20
		PS032	91.3	207.8-4.5	114	1.1	5.7-0.0	30
		PS033	99.1	286.5-0.2	86	4.6	20.4-0.0	46
	PN	PN008	29.8	214.4-0.0	47	4.3	21.4-0.0	29
		PN009	185.6	472.7-11.4	81	2.6	10.9-0.0	43
		PN011	112.9	383.8-0.0	74	3.1	10.7-0.0	38
		PN017	92.2	349.6-0.4	52	0.6	3.0-0.0	26
	PH	PH036	8.0	35.2-0.0	30	0.4	2.8-0.0	16
		PH040	59.3	222.4-0.0	64	3.7	18.0-0.0	41
		PH041	20.1	135.5-0.0	42	10.1	63.6-0.0	40
PH042		64.7	281.2-0.0	61	2.6	14.8-0.0	22	
Prades	PS	PS343	231.7	538.9-0.0	58	19.6	56.4-0.5	29
		PS344	225.3	551.2-0.0	68	23.2	87.3-0.0	29

	PP301	73.4	267.8-0.0	35	15.3	31.3-0.1	31
PP	PP302	69.3	159.0-0.0	30	39.1	81.0-1.0	26
	PP311	128.2	450.7-0.6	23	11.6	30.9-0.2	42
	PP314	84.5	238.6-0.0	54	11.5	23.1-2.2	35

266

267 The influence of climate on fungal yield differed among functional guilds, tree species,
268 and sites (Fig. 4). Thus, the production of saprotrophic fungi was more sensitive to climate
269 conditions than the MFY under the more xeric conditions (Supplementary Material, Fig. A3). In
270 Solsonès, MFY was significantly influenced by precipitation values in May in the PH plots
271 (positive relationship, Fig. 4). In Prades, MFY was enhanced by high values of maximum
272 temperature in March in the PS plots, but it was reduced by high values of minimum
273 temperatures during the same month in the PP plots. Additionally, MFY was improved by
274 humid conditions in August and September in both PS and PP plots, while it was negatively
275 related to precipitation and water balance during March in the PS plots. The response of MFY to
276 climate variables in the PS plots changed between sites (e.g. the positive influence of humid
277 conditions during summer on MFY in PS plots was only observed in the more xeric Prades
278 area).

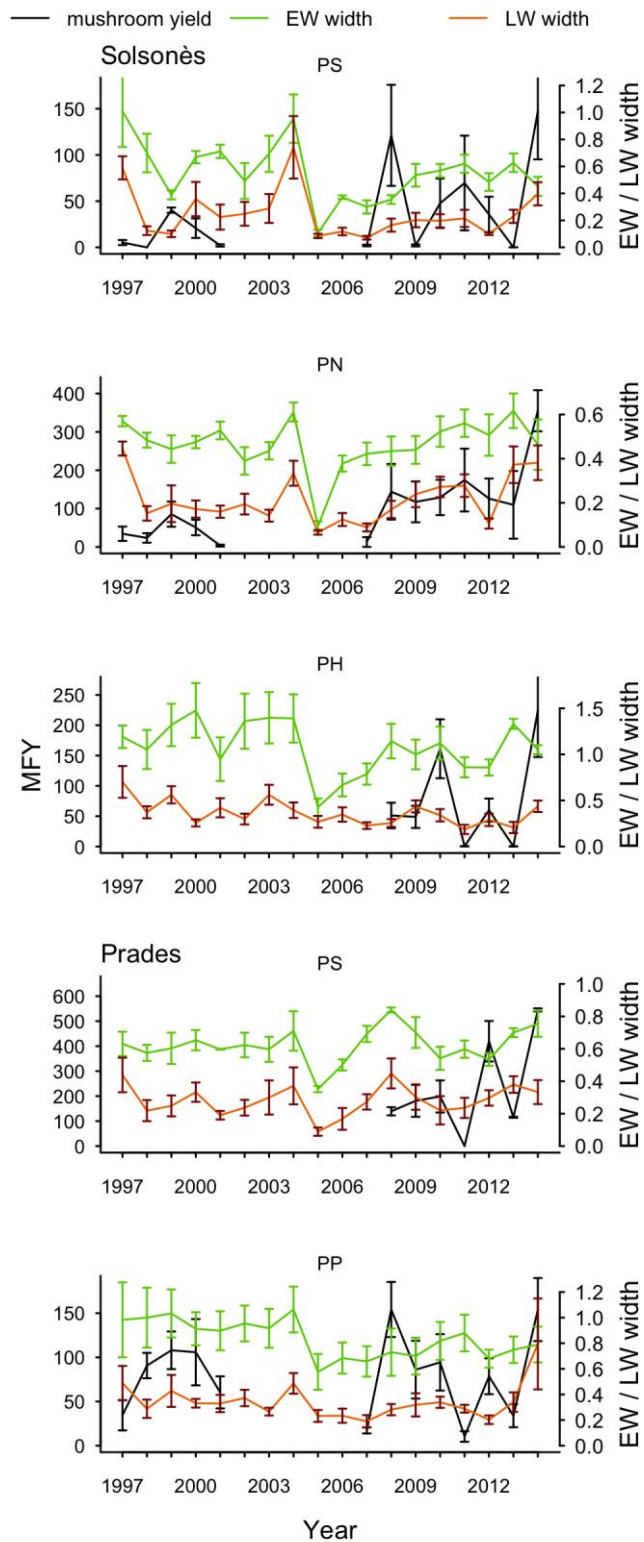


279 **Figure 4.** Correlations (Spearman coefficients) obtained by relating annual mycorrhizal fungi
 280 yield and monthly minimum and maximum temperature, total precipitation, and water balance
 281 (precipitation minus potential evapotranspiration, PET) for each pine species and sample site.
 282 Horizontal dashed lines represent $P < 0.05$ significance levels. Pine species abbreviations are as
 283 in Table 1.

284

285 **3.3. Linkages between mycorrhizal mushroom production and tree growth**

286 In general, no clear temporal coupling was observed between mean annual mycorrhizal
287 fungi yields and EW and LW production excepting for some sites (Fig. 5). Significant
288 relationships between MFY and EW were only found in the Solsonès area, where both negative
289 (some PN and PS plots) and positive (one PN plot) relationships were observed (Table 4).
290 Mycorrhizal fungi yield was related to LW production only in some Prades PP plots (positive
291 associations). When controlling for the main climatic constraints of tree growth (cumulative
292 precipitation from August to September), significant and positive LW-MFY correlations were
293 found for two PP plots in Prades. When controlling for growth effects of EW on LW, positive
294 LW-MFY correlations were observed in Prades (both PP and PS plots) and in some PH and PN
295 plots in Solsonès. Regarding site conditions, correlations and partial correlations between LW
296 and MFY increased when the plot slope decreased (Supplementary Material, Fig. A4).
297



298 **Figure 5.** Temporal trends of mean annual mycorrhizal (MFY) fungi yields (left y axes, fungi
 299 production data are fresh mass in $\text{kg ha}^{-1} \text{ year}^{-1}$) and earlywood (EW) and latewood (LW)
 300 widths (right y axes, data are in mm). Values are means \pm SE. Pine species abbreviations are as
 301 in Table 1.

302

303 **Table 4.** Spearman correlations calculated between earlywood (EW) and latewood widths (LW)

304 and mean annual mycorrhizal fungi yield (MFY). Partial correlations were also calculated

305 between LW and MFY controlling for climatic (cumulative precipitation from August to

306 September) or growth effects (EW). Pine species abbreviations are as in Table 1. Significance

307 levels: * $0.05 < P \leq 0.1$; ** $0.05 < P \leq 0.01$; *** $0.01 < P \leq 0.001$

308

Site	Pine species	Plot	No. years of data	EW vs. MFY	LW vs. MFY	Partial correlations	
						LW vs. MFY controlled for precipitation	LW vs. MFY controlled for EW
Solsonès	PS	29	13	0.44	0.37	0.33	0.09
		30	13	-0.55*	-0.07	-0.12	0.34
		31	13	0.13	0.07	-0.16	0.01
		32	13	-0.23	-0.30	-0.37	-0.21
		33	13	-0.24	0.15	0.06	0.31
	PN	8	13	-0.59*	0.21	0.14	0.52*
		9	13	0.58*	0.47	0.48	0.31
		11	13	-0.05	0.48	0.51	0.53*
		17	13	-0.59*	0.04	0.02	0.58*
	PH	36	13	-0.49	-0.41	-0.47	-0.25
		40	13	-0.11	0.19	0.19	0.32
		41	13	-0.35	0.09	0.04	0.34
		42	13	-0.25	0.40	0.43	0.63**
	Prades	PS	343	7	-0.07	0.04	-0.59
344			7	0.11	0.43	-0.39	0.74*
PP		301	6	0.33	0.64	0.07	0.69
		302	7	-0.36	0.71	0.61	0.85***
		311	7	0.18	0.75*	0.85**	0.76**
		314	7	-0.11	0.82*	0.79***	0.85***

309

310 4. Discussion

311 The novelty of this research is the described connection between wood formation and

312 fungal yields, and characterizing how this link depends on climate variability. The climate

313 signal on tree-ring features and mushroom productivity varied among host tree species and

314 increased towards the drier sites. In the study sites subjected to the driest summer, mycorrhizal

315 fungal yields increased in response to wet late-summer to fall conditions. These climatic

316 conditions also favoured latewood formation, which explains why latewood production
317 correlated to mycorrhizal fungal yield in such drought-prone sites.

318

319 **4.1. Tree growth responses to climate**

320 Additionally to our first hypothesis (EW and LW mainly driven by climate conditions in
321 spring and in late-summer and fall, respectively), both EW and LW were influenced by climate
322 conditions during previous fall and from April to October. EW was more sensitive to climate
323 variability than LW, agreeing with previous findings in other Mediterranean pine forests (Pasho
324 et al., 2012). EW formation was enhanced by cold and wet climate conditions during the
325 previous fall and winter, and current spring and summer. LW responded to temperature
326 (negatively) and precipitation (positively) from spring to early fall indicating that wet and cool
327 conditions during the late growing season favour carbon use in radial growth and tracheid cell-
328 wall thickening and lignifications, as it has been also observed in Corsican pine stands in
329 western France (Lebourgeois, 2000). The responses of both EW and LW to climate were site
330 and species specific, showing an increasing influence of summer conditions in the more xeric
331 sites subjected to Mediterranean conditions (Prades study area).

332

333 **4.2. Mycorrhizal mushroom production and its response to climate**

334 In the more xeric Prades study area, mycorrhizal fungi were less climate-dependent than
335 saprotrophic fungi, as it has been already described previously (Boddy et al., 2014; Diez et al.,
336 2013). Due to the symbiotic associations with tree roots, the mycelium of mycorrhizal fungi
337 may explore deeper soil layers than the saprotrophic fungi mycelium, which mainly occupies
338 the organic soil layer (Diez et al., 2013). Additionally, the ecology of mycorrhizal fungi is
339 influenced by the fungi-tree interactions (e.g. transfer of nutrients and carbohydrates between
340 trees roots and fungi in the rizosphere; Boddy et al., 2014), and by the performance of trees (e.g.
341 leaf and root phenology, photosynthetic activity and carbon use). For instance, water may be
342 transferred from the hosts to their mycorrhizal simbionts in response to drought stress
343 (Querejeta et al., 2003). Therefore, the production of mycorrhizal fungi may be expected to rely

344 less on climate conditions than saprotrophic fungi, even though similar direct climate controls
345 on the fruit body production of both functional guilds have been also suggested (Büntgen et al.,
346 2013).

347 The different response of fungi production to climate among the species \times site
348 combinations were probably related to elevation-induced changes in the local climate conditions
349 (Pinna et al., 2010). Thus, the higher sensitivity of mushroom production to summer
350 precipitation observed in the Scots pine plots located in Prades (elevational range: 841 – 864 m)
351 than those in Solsonès (elevational range: 854 – 1502 m) might have been related to a higher
352 drought stress in Prades sites linked to lower elevation. Indeed, previous studies suggest that
353 temperature influences fungal activity under humid climate regimes, while water availability
354 gains importance towards drier sites (e.g. Bonet et al., 2010; Büntgen et al., 2012; de-Miguel et
355 al., 2014). Accordingly, de-Miguel et al. (2014) discussed that mushroom production may
356 decrease towards higher elevations because of low temperature constraints, even though water
357 availability increases. However, in our study, mushroom production was not apparently
358 restricted by low temperatures in the Scots pine plots located in the mesic Solsonès area,
359 probably because there were not plots in temperate or precipitation- limited conditions and also,
360 due to the limitation of the climatic data used in this study, being assigned the same climatic
361 data to all the Solsonès plots.

362

363 **4.3. Linkages between mycorrhizal mushroom production and seasonal wood formation**

364 Mycorrhizal mushroom yield was frequently coupled with latewood width production,
365 particularly in sites under severe summer drought conditions. The production of mycorrhizal
366 fruiting bodies is highly dependent on the transfer of current photosynthates from the tree to the
367 fungi (Högberg et al., 2008). Thus, disturbances which reduce that photosynthates transfer such
368 as defoliation have been found to affect ectomycorrhizal fungi fruiting (Kuikka et al., 2003).

369 Tree secondary growth could be therefore expected to be associated with mycorrhizal
370 fungi fruiting if carbon allocation rates to roots and stem wood are tightly related. In this
371 framework, the production of ectomycorrhizal fruiting bodies has been suggested to increase

372 with the photosynthetic capacity of the associated trees (Egli et al., 2010), while when studying
373 plots covering a range of stand basal areas, mushroom production is maximum when the annual
374 increment of the stand basal area peaks (Bonet et al., 2010, 2008). Tree growth-fungi fruiting
375 relationships have been previously investigated in thinning experiments, but contrasting
376 responses of mycorrhizal fungi yield after thinning have been obtained (e.g. Bonet et al., 2012;
377 Egli et al., 2010; Pilz et al., 2006). Additionally, cautious should be taken when investigating
378 growth- fungi associations after thinning since fungi yields may also depend on the season,
379 pattern and intensity of the thinning (Egli et al., 2010; Luoma et al., 2004).

380 Based on an in-vitro experiment, Fortin et al. (2008) suggested that the onset of the
381 mushroom season occurs when the terminal buds of associated trees are developed at the
382 beginning of fall, when the mobile carbon pool in the roots is nearly twice than in spring (Li et
383 al., 2002). Furthermore, in conifers current-year photoassimilates are mainly used in latewood
384 formation, while carbohydrates synthesized from the previous summer and fall and current
385 spring are mainly involved in earlywood formation (Kagawa et al., 2006). Consequently, we
386 hypothesized that mycorrhizal fungi production during fall could be linked to latewood width
387 rather than with earlywood or tree-ring width. According to that hypothesis, we did find positive
388 and significant relationships between mycorrhizal fungi production and latewood width, the
389 number of these relationships being highest when controlling for the growth effects on the latter.
390 Significant associations were frequently found in PN plots in Solsonès and PP plots in Prades,
391 probably related to the carbon use within trees and water limitations during the growing season,
392 as it has been already suggested by Büntgen et al. (2015). They found similar responses between
393 mycorrhizal fungi production and latewood width in a Scots pine forest located in Central Spain
394 under Mediterranean and continental conditions. Indeed, the observed associations between
395 mycorrhizal fungi production and latewood width increased when the plot slope decreased,
396 probably due to higher water or nutrient availability.

397 The relationships between mycorrhizal fungi production and latewood formation may be
398 disguised by several reasons. First, fungi species may show contrasting associations with their
399 hosts, similarly to the observed greatly variable responses to climate conditions (e.g. Boddy et

400 al., 2014). Second, host activity may influence mycelium production rather than mushroom
401 fruiting, while the relationships between them remains broadly uncertain, and multiple
402 environmental and biotic factors may affect fungi fruiting (Diez et al., 2013). Third, even
403 though mycorrhizal fungi gain carbon mainly from their hosts, they may also obtain carbon by
404 decomposing soil organic matter (Talbot et al., 2008). Therefore, significant relationships
405 between fungi production and tree growth are difficult to find, probably because of the complex
406 links existing between environmental constraints, mushroom production and tree growth
407 phenology (Büntgen et al., 2013). Consequently, although we did not find significant
408 associations in all the study plots, our results are a valuable contribution in the understanding of
409 the long-term relationships between tree growth and fungi production.

410 To conclude, our findings indicate that latewood variables from tree species located in
411 forests subjected to seasonal summer drought presents linkages with fungal yields in
412 Mediterranean pine forests. Therefore, latewood production is a promising proxy of fungal yield
413 in drought-prone forests. Further research is required to disentangle the links between climate,
414 tree growth and mushroom production including seasonal assessments of wood formation,
415 carbon use and changes in biomass of the soil mycelium.

416

417 **Acknowledgements**

418 This study was partially funded by the research project AGL2012-40035-C03-01
419 (Ministerio de Economía y Competitividad of Spain, Secretaría de Estado de Investigación,
420 Desarrollo e Innovación), by the European project “StarTree – Multipurpose trees and non-
421 wood forest products: a challenge and opportunity” under grant agreement No. 311919. Irantzu
422 Primicia work was supported by a STSM Grant from the COST Action FP1203 (European Non-
423 Wood Forest Products).

424

425 **References**

- 426 Ágreda, T., Águeda, B., Olano, J.M., Vicente-Serrano, S.M., Fernández-Toirán, M., 2015.
427 Increased evapotranspiration demand in a Mediterranean climate might cause a decline in
428 fungal yields under global warming. *Glob. Chang. Biol.* 21, 3499–3510.
429 doi:10.1111/gcb.12960
- 430 Beguería, S., Vicente-Serrano, S.M., Reig, F., Latorre, B., 2014. Standardized precipitation
431 evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models,
432 tools, datasets and drought monitoring. *Int. J. Climatol.* 34, 3001–3023.
433 doi:10.1002/joc.3887
- 434 Boddy, L., Büntgen, U., Egli, S., Gange, A.C., Heegaard, E., Kirk, P.M., Mohammad, A.,
435 Kauserud, H., 2014. Climate variation effects on fungal fruiting. *Fungal Ecol.* 10, 20–33.
436 doi:10.1016/j.funeco.2013.10.006
- 437 Bonet, J.A., de-Miguel, S., Martínez de Aragón, J., Pukkala, T., Palahí, M., 2012. Immediate
438 effect of thinning on the yield of *Lactarius* group *deliciosus* in *Pinus pinaster* forests in
439 North-Eastern Spain. *For. Ecol. Manage.* 265, 211–217. doi: 10.1016/j.foreco.2011.10.039
- 440 Bonet, J.A., Fischer, C.R., Colinas, C., 2004. The relationship between forest age and aspect on
441 the production of sporocarps of ectomycorrhizal fungi in *Pinus sylvestris* forests of the
442 central Pyrenees. *For. Ecol. Manage.* 203, 157–175. doi:10.1016/j.foreco.2004.07.063
- 443 Bonet, J.A., González-Olabarria, J., Martínez de Aragón, J., 2014. Mushroom production as an
444 alternative for rural development in a forested mountainous area. *J. Mt. Sci.* 11(2).
445 doi:0.1007/S11629-013-2877-0
- 446 Bonet, J.A., Palahí, M., Colinas, C., Pukkala, T., Fischer, C.R., Miina, J., Martínez de Aragón,
447 J., 2010. Modelling the production and species richness of wild mushrooms in pine forests
448 of the Central Pyrenees in northeastern Spain. *Can. J. For. Res.* 40, 347–356.
449 doi:10.1139/X09-198
- 450 Bonet, J.A., Pukkala, T., Fischer, C.R., Palah, M., De, J.M., Colinas, C., 2008. Empirical
451 models for predicting the production of wild mushrooms in Scots pine (*Pinus sylvestris* L.)
452 forests in the Central Pyrenees. *Ann. For. Sci.* 65, 1–9. doi:10.1051/forest

453 Büntgen, U., Egli, S., 2014. Breaking new ground at the interface of dendroecology and
454 mycology. *Trends Plant Sci.* 19, 613–614. doi:10.1016/j.tplants.2014.07.001

455 Büntgen, U., Egli, S., Galván, J.D., Diez, J.M., Aldea, J., Latorre, J., Martínez-Peña, F., 2015.
456 Drought-induced changes in the phenology, productivity and diversity of Spanish fungi.
457 *Fungal Ecol.* 16, 6–18. doi:10.1016/j.funeco.2015.03.008

458 Büntgen, U., Kauserud, H., Egli, S., 2012. Linking climate variability to mushroom productivity
459 and phenology. *Front. Ecol. Environ.* 10, 14–19. doi:10.1890/110064

460 Büntgen, U., Peter, M., Kauserud, H., Egli, S., 2013. Unraveling environmental drivers of a
461 recent increase in Swiss fungi fruiting. *Glob. Chang. Biol.* 19, 2785–2794.
462 doi:10.1111/gcb.12263

463 Camarero, J.J., Olano, J.M., Parras, A., 2010. Plastic bimodal xylogenesis in conifers from
464 continental Mediterranean climates. *New Phytol.* 185, 471–480. doi:10.1111/j.1469-
465 8137.2009.03073.x

466 de-Miguel, S., Bonet, J.A., Pukkala, T., Martínez de Aragón, J., 2014. Impact of forest
467 management intensity on landscape-level mushroom productivity: A regional model-based
468 scenario analysis. *For. Ecol. Manage.* 330, 218–227. doi:10.1016/j.foreco.2014.07.014

469 Dickie, I. a., Kałucka, I., Stasińska, M., Oleksyn, J., 2010. Plant host drives fungal phenology.
470 *Fungal Ecol.* 3, 311–315. doi:10.1016/j.funeco.2009.12.002

471 Diez, J.M., James, T.Y., Mcmunn, M., Ibáñez, I., 2013. Predicting species-specific responses of
472 fungi to climatic variation using historical records. *Glob. Chang. Biol.* 19, 3145–3154.
473 doi:10.1111/gcb.12278

474 Dixon, P., 2001. Bootstrap resampling, in: El-Shaarawi, AH, Piegorisch, W. (Ed.), *The*
475 *Encyclopedia of Environmetrics*. Wiley, New York.

476 Egli, S., Ayer, F., Peter, M., Eilmann, B., Rigling, A., 2010. Is forest mushroom productivity
477 driven by tree growth? Results from a thinning experiment. *Ann. For. Sci.* 67, 509–509.
478 doi:10.1051/forest/2010011

479 Fortin, J., Plenchette, C., Piché, Y., 2008. *Les mycorhizes, la nouvelle révolution verte.*
480 Édition Multimondes, Québec, Canada.

481 Fritts, H.C., 2001. *Tree-Rings and Climate*. Blackburn Press, Caldwell, NJ, USA.

482 Gange, A.C., Gange, E.G., Sparks, T.H., Boddy, L., 2007. Rapid and Recent Changes in Fungal
483 Fruiting Patterns. *Science* 316, 71. doi:10.1126/science.1137489

484 Gerdemann, J., 1970. The significance of vesicular-arbuscular mycorrhizae in plant nutrition, in:
485 Toussoun, T., Bega, R., Nelson, P. (Eds.), *Root Diseases and Soil-Borne Plant Pathogens*.
486 University of California Press, Berkeley, USA, pp. 125–129.

487 Hargreaves, G.H., Samani, Z.A., 1982. Estimating potential evapotranspiration. Technical note.
488 *J. Irrig. Drain. Eng.* 108, 225–230.

489 Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A
490 European daily high-resolution gridded data set of surface temperature and precipitation for
491 1950–2006. *J. Geophys. Res.* 113, D20119. doi:10.1029/2008JD010201

492 Högberg, P., Högberg, M.N., Göttlicher, S.G., Betson, N.R., Keel, S.G., Metcalfe, D.B.,
493 Campbell, C., Schindlbacher, A., Hurry, V., Lundmark, T., Linder, S., Näsholm, T., 2008.
494 High temporal resolution tracing of photosynthate carbon from the tree canopy to forest
495 soil microorganisms. *New Phytol.* 177, 220–228. doi:10.1111/j.1469-8137.2007.02238.x

496 Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement.
497 *Tree-Ring Bull.* 43.

498 Kagawa, A., Sugimoto, A., Maximov, T.C., 2006. ¹³CO₂ pulse-labelling of photoassimilates
499 reveals carbon allocation within and between tree rings. *Plant, Cell Environ.* 29, 1571–
500 1584. doi:10.1111/j.1365-3040.2006.01533.x

501 Kauserud, H., Stige, L.C., Vik, J.O., Okland, R.H., Høiland, K., Stenseth, N.C., 2008.
502 Mushroom fruiting and climate change. *Proc. Natl. Acad. Sci. U. S. A.* 105, 3811–3814.
503 doi:10.1073/pnas.0709037105

504 Kuikka, K., Härmä, E., Markkola, A., Rautio, P., Roitto, M., Saikkonen, K., Ahonen-Jonnarth,
505 U., Finlay, R., Tuomi, J., 2003. Severe defoliation of Scots pine reduces reproductive
506 investment by ectomycorrhizal symbionts. *Ecology* 84, 2051–2061. doi: 10.1890/02-0359

507 Lebourgeois, F., 2000. Climatic signals in earlywood, latewood and total ring width of Corsican
508 pine from western France. *Ann. For. Sci.* 57, 155–164. doi:10.1051/forest:2000166

509 Li, M., Hoch, G., Korner, C., 2002. Source/sink removal affects mobile carbohydrates in *Pinus*
510 *cembra* at the Swiss treeline. *Trees - Struct. Funct.* 16, 331–337. doi: 10.1007/s00468-002-
511 0172-8

512 Luoma, D.L., Eberhart, J.L., Molina, R., Amaranthus, M.P., 2004. Response of ectomycorrhizal
513 fungus sporocarp production to varying levels and patterns of green-tree retention. *For.*
514 *Ecol. Manage.* 202, 337–354. doi:10.1016/j.foreco.2004.07.041

515 Martínez de Aragón, J., Bonet, J.A., Fischer, C.R., Colinas, C., 2007. Productivity of
516 ectomycorrhizal and selected edible saprotrophic fungi in pine forests of the pre-Pyrenees
517 mountains, Spain: Predictive equations for forest management of mycological resources.
518 *For. Ecol. Manage.* 252, 239–256. doi:10.1016/j.foreco.2007.06.040

519 Martínez-Peña, F., Ágreda, T., Águeda, B., Ortega-Martínez, P., Fernández-Toirán, L.M., 2012.
520 Edible sporocarp production by age class in a Scots pine stand in Northern Spain.
521 *Mycorrhiza* 22, 167–174. doi:10.1007/s00572-011-0389-8

522 Pasho, E., Julio Camarero, J., Vicente-Serrano, S.M., 2012. Climatic impacts and drought
523 control of radial growth and seasonal wood formation in *Pinus halepensis*. *Trees* 26, 1875–
524 1886. doi:10.1007/s00468-012-0756-x

525 Pilz, D., Molina, R., Mayo, J., 2006. Effects of thinning young forests on *Chanterelle*
526 mushroom production. *J. For.* 104, 9–14.

527 Pinna, S., Gévry, M.F., Côté, M., Sirois, L., 2010. Factors influencing fructification phenology
528 of edible mushrooms in a boreal mixed forest of Eastern Canada. *For. Ecol. Manage.* 260,
529 294–301. doi:10.1016/j.foreco.2010.04.024

530 Querejeta, J.I., Egerton-Warburton, L.M., Allen, M.F., 2003. Direct nocturnal water transfer
531 from oaks to their mycorrhizal symbionts during severe soil drying. *Oecologia* 134, 55–64.
532 doi:10.1007/s00442-002-1078-2

533 R Core Team, 2015. R: A language and environment for statistical computing. R Foundation for
534 Statistical Computing, Vienna, Austria.

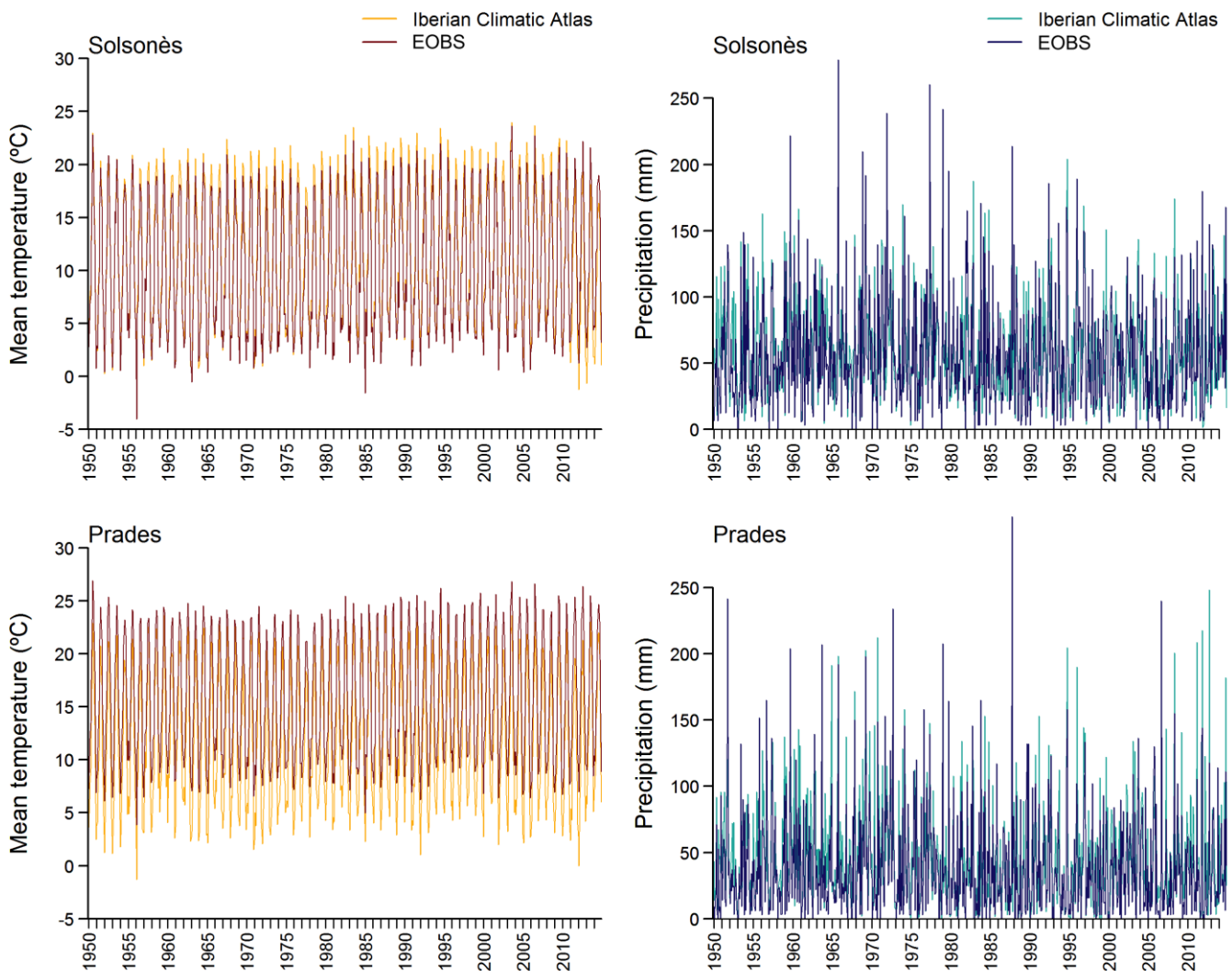
- 535 Tahvanainen, V., Miina, J., Kurttila, M., Salo, K., 2016. Modelling the yields of marketed
536 mushrooms in *Picea abies* stands in eastern Finland. *For. Ecol. Manage.* 362, 79–88.
537 doi:10.1016/j.foreco.2015.11.040
- 538 Talbot, J.M., Allison, S.D., Treseder, K.K., 2008. Decomposers in disguise: Mycorrhizal fungi
539 as regulators of soil C dynamics in ecosystems under global change. *Funct. Ecol.* 22, 955–
540 963. doi:10.1111/j.1365-2435.2008.01402.x
- 541 Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index
542 sensitive to global warming: The standardized precipitation evapotranspiration index. *J.*
543 *Clim.* 23, 1696–1718. doi:10.1175/2009JCLI2909.1
- 544

545 **SUPPLEMENTARY MATERIAL**

546 **Linkages between climate, seasonal wood formation and mycorrhizal**
547 **mushroom yields**

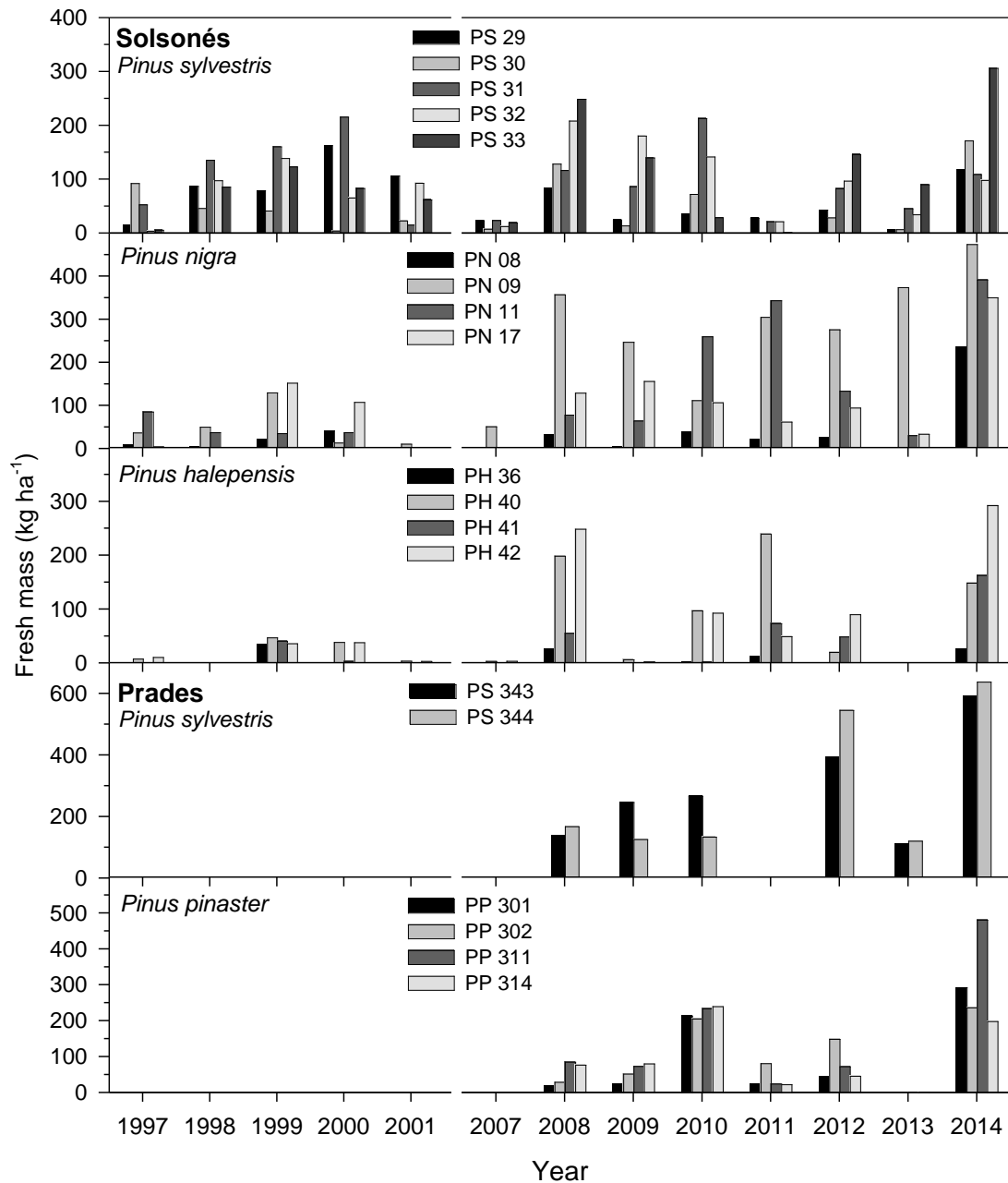
548 Irantzu Primicia, J. Julio Camarero, Juan Martínez de Aragón, Sergio de-Miguel and José Antonio

549 Bonet



550 **Figure A1.** Mean annual temperature and annual precipitation recorded in the two study
551 areas (Solsonès, Prades) and considering the 1950-2014 period. Compared data correspond to
552 the Iberian Climatic Atlas (Ninyerola et al., 2005) and the European E-OBS 0.25°-gridded
553 (Haylock et al., 2008) data sets.

554



555

556

557 **Figure A2.** Mean annual mycorrhizal mushroom yield data recorded in five pine species

558 from the two study areas. Pine species abbreviations: PS: *P. sylvestris*, PN: *P. nigra*, PH: *P.*

559 *halepensis*, PP: *P. pinaster*.

560

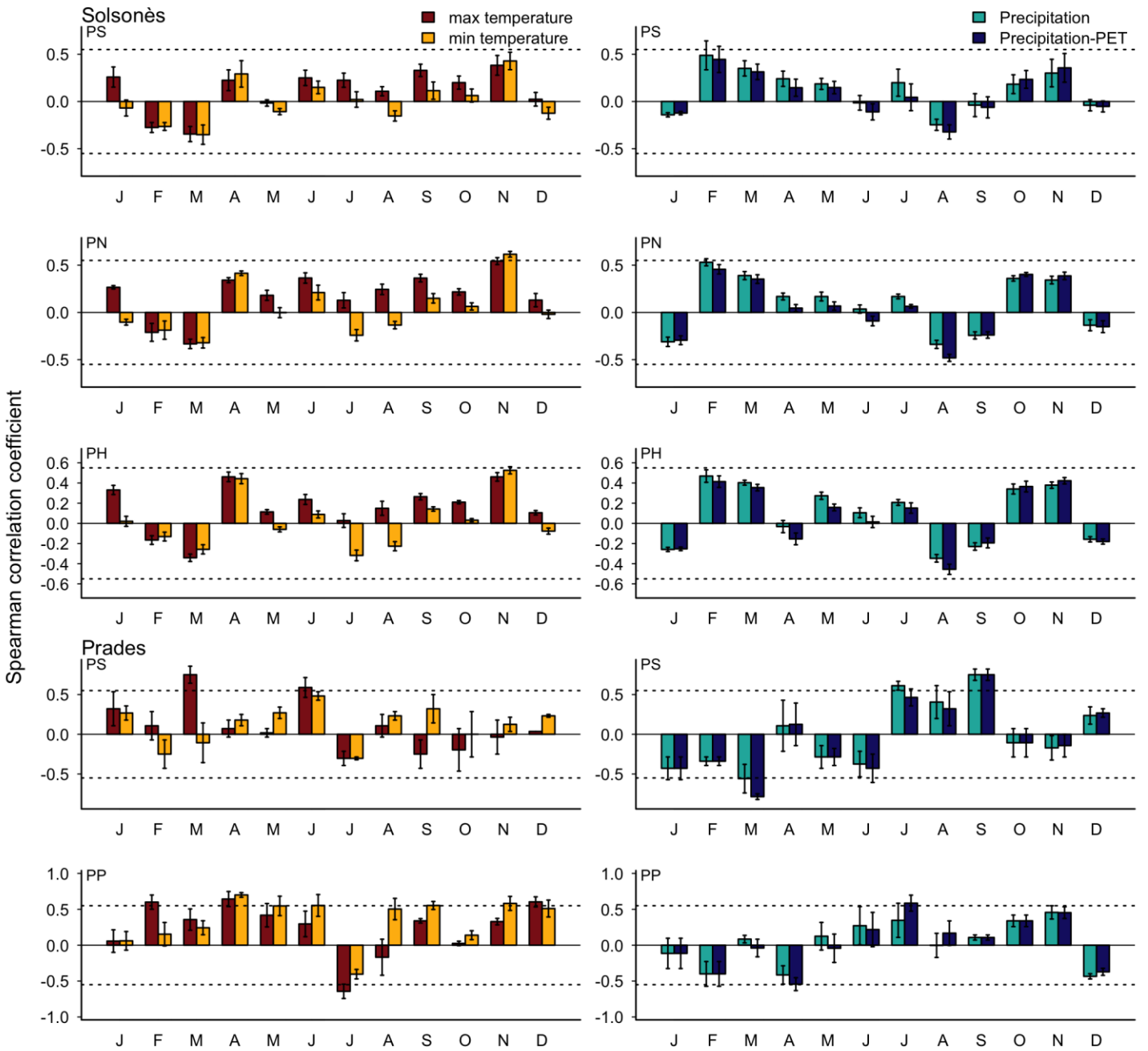
561

562 **Table A1.** Ten most abundant fungal species (kg ha⁻¹ yr⁻¹) recorded in each study site
 563 considering different pine species.

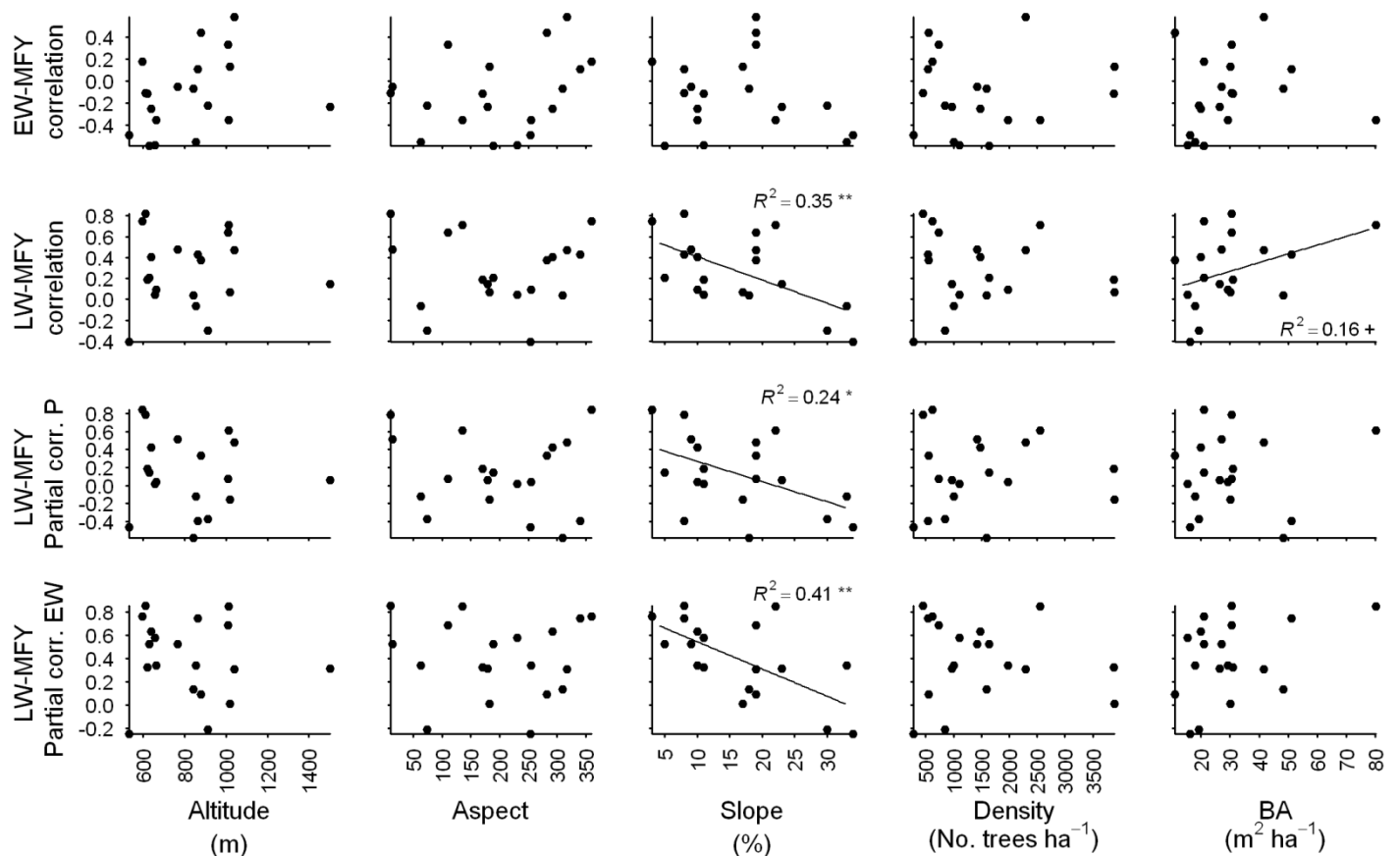
Site	Pine species	Fungal Species
	Scots pine , <i>Pinus sylvestris</i>	<i>Tricholoma fracticum</i> (Batsch) Kreisel, <i>Suillus variegatus</i> (Swartz) Rich. & Roze., <i>Suillus luteus</i> (L.) Roussel., <i>Hydnum repandum</i> L., <i>Russula torulosa</i> Bres., <i>Hygrophorus latitabundus</i> Britz., <i>Lactarius deliciosus</i> (L.) S. F. Gray, <i>Hebeloma edurum</i> Métrod ex M. Bon, <i>Suillus collinitus</i> (Fr.) Kuntze, <i>Lactarius sanguifluus</i> (Paul.) Fr.
Sols onès	Black pine, <i>Pinus nigra</i>	<i>Chroogomphus rutilus</i> (Sch.) Miller, <i>Suillus granulatus</i> (L.) Roussel., <i>Tricholoma fracticum</i> (Batsch) Kreisel, <i>Hygrophorus latitabundus</i> Britz., <i>Cantharellus lutescens</i> Fr., <i>Lactarius deliciosus</i> (L.) S. F. Gray, <i>Suillus collinitus</i> (Fr.) Kuntze, <i>Amanita ovoidea</i> (Bull.) Link., <i>Paxillus atrotomentosus</i> (Batsch) Fr., <i>Suillus luteus</i> (L.) Roussel.
	Aleppo pine, <i>Pinus halepensis</i>	<i>Hydnum repandum</i> L., <i>Hygrophorus latitabundus</i> Britz., <i>Tricholoma fracticum</i> (Batsch) Kreisel, <i>Tricholoma caligatum</i> (Viv.) Ricken., <i>Cantharellus lutescens</i> Fr., <i>Russula sanguinea</i> (Bull. ex St. Amans) Fr., <i>Lactarius deliciosus</i> (L.) S. F. Gray, <i>Suillus collinitus</i> (Fr.) Kuntze, <i>Suillus granulatus</i> (L.) Roussel., <i>Lactarius chrysorrheus</i> Fr.
Prad es	Scots pine , <i>Pinus sylvestris</i>	<i>Lactarius vellereus</i> (Fr.) Fr., <i>Russula chloroides</i> (Kromb.) Bres., <i>Lactarius chrysorrheus</i> Fr., <i>Lactarius deliciosus</i> (L.) S. F. Gray, <i>Russula delica</i> Fr., <i>Ramaria aurea</i> (Sch.) Quéł., <i>Macrolepiota procera</i> (Scop.) Sing., <i>Lactarius violascens</i> (Otto) Fr., <i>Mycena zephirus</i> (Fr.) Kumm., <i>Russula sanguinea</i> (Bull. ex St. Amans) Fr.
	Maritime pine, <i>Pinus pinaster</i>	<i>Suillus granulatus</i> (L.) Roussel., <i>Lactarius vellereus</i> (Fr.) Fr., <i>Macrolepiota procera</i> (Scop.) Sing., <i>Tricholoma terreum</i> (Sch.) Kumm., <i>Chroogomphus rutilus</i> (Sch.) Miller, <i>Leucopaxillus gentianeus</i> (Quéł.) Kotl., <i>Lactarius vinosus</i> Quéł., <i>Rhodocollybia butyracea</i> (Bull.) Kumm., <i>Mycena seynesii</i> Quéł., <i>Lactarius deliciosus</i> (L.) S. F. Gray

564

565



567 **Figure A3.** Correlations (Spearman coefficients) obtained by relating between mean
 568 annual saprotrophic fungi yield and monthly minimum and maximum temperature,
 569 precipitation, and water balance (precipitation minus potential evapotranspiration, PET)
 570 variables for each tree species and sample site. Horizontal dashed lines represent $P < 0.05$
 571 significance levels. Pine species abbreviations are as in Figure A2.



573 **Figure A4.** Linear relationships (Spearman correlation coefficients) between earlywood
 574 (EW) and latewood widths (LW) and mean annual mycorrhizal fungi yield (MFY), and partial
 575 correlations calculated between LW and MFY by controlling for climatic (cumulative
 576 precipitation from August to September- P) or growth effects (EW) and plots characteristics.
 577 Abbreviations: BA, basal area. Significance levels: * $P \leq 0.05$; ** $0.05 < P \leq 0.01$; *** $0.01 < P \leq$
 578 0.001

579

580 **References**

581 Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A
 582 European daily high-resolution gridded data set of surface temperature and precipitation for
 583 1950–2006. *J. Geophys. Res.* 113, D20119.

584 Ninyerola M., Roure J.M. and Pons, X. 2005. Atlas climático digital de la Península Ibérica:
 585 metodología y aplicaciones en bioclimatología y geobotánica. Centre de Recerca Ecològica i
 586 Aplicacions Forestals, Bellaterra, Barcelona, Spain.

587